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A review: Energy recovery in batch processes

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ABSTRACT

The implementation of batch processing has increased due to its intrinsic flexibility and adaptability. These are essential characteristics when it comes to producing high-value added materials such as agrochemicals, pharmaceuticals, specialty chemicals. . .the demand for which has grown in recent decades.

Although industrial processes are highly diverse, a common feature to all is that they utilize fossil fuels as the energy source. The reliance on fossil fuels as a primary source of energy generates a negative impact on the environment. The implantation of renewable energies and efficient usage of energy has thus become crucial. Improving energy use could be achieved through advancements in plant machinery and the use of methodologies such as 'process integration'.

Process integration can be described as system oriented methods that could be used during the design and retrofit of industrial processes in order to obtain an optimal utilization of resources. The methods have traditionally focused on an efficient energy use, although recently process integration techniques cover other areas such as efficient use of raw materials, emission reduction and process operations. Energy integration tries to reach the optimization of heat, power, fuel and utilities.

The consideration of energy integration complicates the process design and the generation of batch process design alternatives, so what is now required is the proposal and development of different approaches and methods oriented towards recovering energy in this kind of industrial process. Improving energy end-use efficiency will make it possible to reduce dependence on energy imports and bring about innovation and competitiveness.

The aim of this work is report the main contributions that have been carried out in order to attain energy integration in batch processes, as well as different examples of applications that have shown the possibilities offered by the developed tools.

Contents

1. Introduction

The process industries usually require enormous quantities of mass and energy [1] and there has been a trend towards an increase in global raw materials and energy consumption. This makes the environment more vulnerable in terms of environmental problems [2]. Thus the use of energy and raw materials in process industries urgently requires both a more efficient management

Abbreviations: GA, genetic algorithm; GCC, grand composite curves; HEN, heat exchanger network; HSUs, heat storage units; HTM, heat transfer medium; MILP, mixed integer linear programming; MINLP, mixed integer nonlinear programming; PCM, phase change material; RTN, resource-task network; SSN, state sequence network; TAM, time average model; TSM, time slice model.

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and a minimization of waste in order to fulfil environmental regulations [3,4]. These environmental regulations are the result of public awareness about resource shortages and sustainable development. The current trend shows that the industries are working on waste reduction and an improvement in processes sustainability. This is because the efficient use of resources is recognised as a key element of sustainable development and an effective strategy to reduce negative environmental impacts and production costs.

Industrial plants have continuous and/or batch processing. The implementation of the latter has increased over the last few decades due to its intrinsic flexibility and adaptability. Batch processes consist of a set of operations which are carried out over a period of time on a separate, identifiable item or parcel of material [5]. The flexibility and adaptability of batch processes are essential to produce high-value added materials such as agrochemicals, pharmaceuticals, foods and fine and specialty chemicals, the demand for which has risen in recent decades [6–9].

Industrial activity accounts for around one third of global energy consumption. Although industrial processes are highly diverse, a common feature to them all is that they utilize fossil fuels as an energy source. The reliance on fossil fuels as a primary source of energy generates a negative impact on the environment. Different studies have proved that the main cause of global warming is the emission of greenhouse gases, which are emitted during the burning of fossil fuel [7]. Thus, in order to lessen the impact on the environment and attain economic performance. The implantation of alternative energy sources and efficient usage and transformation of energy is needed. Improving energy use could be achieved through advancements in plant machinery and the use of methodologies such as 'process integration' [10].

Process integration could be described as system oriented methods that can be used during the design and retrofit of industrial process in order to obtain an optimal use of resources. The methods have traditionally focused on an efficient energy use, but recently process integration techniques cover other areas such as efficient use of raw materials, emission reduction and process operations. Process integration has developed different tools and methods, the objective of which is to help in decision making [10,11]. Energy integration focuses on the optimization of heat, power, fuel and utilities [12,13].

The increase in environmental concern and energy cost has enabled industry to reduce energy consumption. In the past, batch industries could tolerate these high inefficiencies due to the high value of final products. However, the emphasis on process sustainability, global price competition and escalating energy costs have incentivized batch industries to consider different measures (raw material and energy reduction, switching to renewable feedstock, waste minimization, recycling...) [14].

Considering heat integration in early design stages of batch processing can lead to more efficient designs. Therefore, efficient models could be decision-making tools which make design easier [15]. However, energy savings in batch plants were neglected in the past because it was believed that they were not as large in magnitude as in continuous cases [16]. This thought was the result of considering batch plants less energy-intensive compared to their continuous production counterparts, which is untrue for some batch operations (dairy products, brewing, and biochemical) [17]. Fortunately, nowadays, new strategies, characterized by the detailed description of the discontinuous process have been proposed to incorporate heat integration considerations in multiproduct and multipurpose plants [18].

Furthermore, heat integration is sometimes far more likely to be carried out to save energy in batch processes because of the lack of heat recovery in them. Simultaneous consideration of production scheduling and heat recovery opportunity becomes an attractive subject in batch plants [9].

The flexibility of batch processes leads to extra complexity in the design and operation of the plant. As multiple tasks can be performed by the same equipment, optimal task scheduling becomes absolutely crucial for meeting production in a cost-effective manner.

In the simplest form, the aim of heat integration is to establish matches between streams that require cooling and those that require heating in order to minimize the use of external utilities (cooling water and steam).

Heat integration is an essential aspect of all industrial processes due to its ability to reduce the amount of hot and cold utilities consumed and, consequently, lower the operating costs. While conventional pinch analysis has been successful in providing solutions for continuous processes, a different method is required to highlight the optimal design for non-continuous and variable rate processes because heat recovery in a batch process is constrained by temperature and time [19,20]. For this reason, different methods, tools, and mathematical models have been developed since the 80's. The aim of this paper is to review the main works that have been done in order to achieve energy integration in batch processes as well as different examples that show the results obtained once developed tools have been implemented in real situations. Section 2 describes some of the more specific features of batch processing and the main ways that could be implemented in heat recovery. The following section draws together different approaches which have been developed to achieve heat recovery in recent decades. The final section focuses on conclusions.

2. Batch process

Batch plants could be used to produce a variety of products by sharing resources (equipment, raw materials, manpower, utilities...) over time. This offers an operational flexibility, which makes this kind of process attractive when product demands change quickly, or when small productions are needed [21].

Batch processing works in a discontinuous mode and is used by the pharmaceutical, polymer, food, speciality chemical industries...on account of its suitability and flexibility when it comes to producing small quantities of high-value products [22]. This kind of process enables a process to be modified without there being any significant equipment changes, which is essential in the current market. Batch processes are characterized by the following [5]:

- Manufacturing operations are executed independently in batches.
- Resource sharing (steam, electricity, auxiliary equipment...).
- Multipurpose equipment (e.g., a piece of equipment could be used as a storage unit or as a processing unit).
- Flexibility (equipment may be connected in different ways).

Batch processing flexibility is highly complex when these plants have to be designed because it is necessary to take into account the requirements and constraints of the corresponding production facilities (safety considerations, technical limitations, short-term availability of units...) [23]. Thus, it is essential the development of tools that make easier their design and optimization [21].

There are a great number of works that have proposed different methodologies aimed at increasing batch process efficiency. These approaches include: make-span reduction and annual throughput maximization [24–27]; process measurements [28,29]; freshwater and wastewater minimization through the exploitation of inter- and intra-process water reuse, batch schedules optimization and/or wastewater treatment [30–35]; reduction of waste generation [36,37]; decreasing the necessity of resources [38,39];

environmental impact assessment [40]; heat recovery...and/or integration of some of these approaches. For example, Linainger et al. created Batch Design Kit which integrated ecological (health, safety, environmental impact) and economic issues [41]. This work represented an on-going research effort to develop methodologies and computerized tools for the conceptual development and design of new batch processes for the manufacturing of pharmaceuticals and specialty chemicals. Another work that combined different approaches in order to improve performance of batch processes was presented by Puigjaner et al. [42]. They created a software package to be used in conjunction with a methodology that they had previously developed [43]. This methodology made it possible to define an overall objective function for the scheduling problem, in which not only the water use was considered, but also the costs associated to water management together with other considerations such as productivity or energy in batch process industries. The global water demand was minimized by a combined heuristic-mathematical optimization procedure and energy recovery was achieved by means of either heat exchangers or direct stream mixing in the spent water tanks. Heat exchange between hot and cold streams could take place among water and non-water streams, whereas direct mixing could only be applied to water streams when contamination constraints were also satisfied. The hot and cold utility to be consumed in conditioning water streams was calculated showing the potential energy recovery that could be achieved when considering water tanks. Energy integration between hot and cold streams was realised by a program module that contained the implementation of the batch energy integration methodology based on task delays [44,45].

In batch processes, the production schedule is critical to achieving overall productivity and economic effectiveness because these processes are time-dependent [46]. A production schedule specifies the sequence in which products have to be produced as well as the times at which the processing operations should be carried out. For this reason, scheduling plays a huge role in heat integration and represents a tool which could help to reduce energy consumption in batch processing.

Thermal integration has been widely applied in continuous processes where substantial energy and capital savings have been obtained. Thermal integration has had less impact on batch processing because the heat sources and sinks tend to be available at different times in the process. However, in recent decades several studies and different projects, as Pilavachi explained in his work [47], have been developed in order to decrease the use of heat in batch processes. There are two forms of heat integration (Fig. 1):

- *Direct heat integration*: This represents the existence of heat exchanges between process streams which co-exist in time, since this mode of heat recovery requires strict scheduling conditions to guarantee product quality and energy efficiency [48].
- *Indirect heat integration*: The heat from hot process streams is first transferred to a heat transfer medium (HTM) which is then heated up and stored until heat is finally transferred to cold process streams whenever needed. This method means that the heat exchange between non-coexistent process streams becomes less limited, so it is less schedule-sensitive and it could provide a great deal of operating flexibility [5].

There are some contributions that consider the mixed mode (mixed direct–indirect heat integration) and explore the complex costs trade-off effects between both modes. In these approaches, the likely variations of schedule must be modelled and explicitly accounted for [49].

The potential for energy saving in batch plants requires academic and industrial efforts in the area of process systems engineering to cope with the time-dependent existence of process hot/cold streams which represent the huge challenge of heat integration in batch plants [7]. The next section describes the main works that have developed different methods, tools... in order to achieve heat integration in a discontinuous process.

3. Heat recovery in batch processes

Heat integration has been widely implemented in industrial processes, as can be seen by the information gathered by some authors [2,50]. These papers collect different experiences with energy saving through the design and application of different methods and tools whose aim is to synthesize heat exchanger networks more efficiently. The experiences included in these papers mainly focus on the continuous process, where the huge interest in heat integration to obtain an efficient process began in the 70's.

This section describes the main works on batch heat integration that have been carried out since the 80's, when the interest in improving batch process efficiency started. There have been different approaches towards heat recovery attainment, the techniques or methods used being either graphical or mathematical. Both types of methods include different alternatives oriented towards obtaining direct, indirect or mixed heat integration.

3.1. Methods and models developed in 20th Century

Early studies, which focused on heat integration of batch processes, applied methods that had been developed for continuous processing. One of the first works, as Kemp describes in his book [51], were the papers presented by Clayton, who calculated the energy reduction through the composites of the Time Average Model (TAM) [52,53]. This method established that the streams exist simultaneously as if the process was continuous. The TAM composites showed the energy integration potential, but the identified energy targets generally could not be achieved when only direct heat integration was resorted to because the TAM composites do not consider time schedule and they average heat flows over the batch cycle time.

This method was also used by Stoltze et al. to calculate waste-heat recovery potential [54]. Once the heat recovery possibilities had been established a simple combinatorial method was presented and applied over six examples considering only the incorporation of energy stores to achieve the maximum energy-saving targets. These examples showed that the introduction of heat storage by this procedure led to a reduction or elimination of difficulties that had been anticipated with regard to the integration of heat recovery by means of heat storage.

Vaselenak et al. did not take into account the time schedule of the process either. They explored the possibility of heat recovery between a number of tanks which required heating or cooling in order to minimize utility consumption. Co-current, counter-current and combinations of the two were considered [55]. They presented a heuristic procedure to determine best pairing when final temperatures were not limiting and a Mixed Integer Linear Programming (MILP) formulation for the case when they were. They assumed that all tanks were available at the same time.

Obeng and Ashton also applied TAM to carry out the overall plant bottleneck approach [56]. This approach was based on the identification of bottlenecks which prevent the plant from reaching its otherwise achievable performance. Furthermore, they also presented the Time Slice Model (TSM). In this model each batch cycle was divided into different time intervals. In each of these intervals, targets for hot and cold utility consumption and a local pinch temperature could be found by using the problem table algorithm. For calculating minimum utility requirements during a batch period, the utility targets of each interval were added

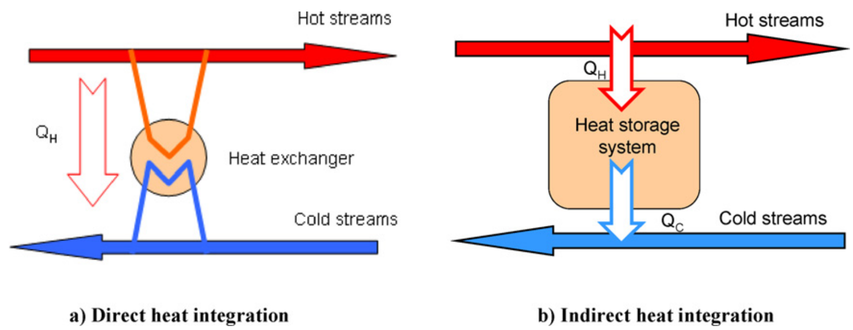

Fig. 1. Forms of heat integration.

together. In this method, it was possible to identify all direct heat exchanges. The result of their work showed that the most sophisticated energy analysis techniques should not be used in isolation. The structure of batch processes meant that integration techniques needed to address the wider problem so that the trade-off between plant capacity, yields, capital and energy costs. . .could be evaluated.

In order to reduce the limitations of the TAM, different works considering the time schedule were done. For example, Kemp and Macdonald developed the time-dependent heat cascade analysis [57]. This new method applied the pinch method to a batch process. Kemp and Macdonald proposed time intervals that allowed the construction of time dependent heat cascades, which in turn provided targets for the amount of heat exchange and heat transfer. Furthermore, analysis of the composite and Grand Composite Curves (GCC) (Fig. 2) pointed the way to beneficial process changes at an early stage. These curves are a graphic representation of the cumulative enthalpy values, obtained from the feasible heat cascades as a function of temperature. The key to batch process analysis was the time-dependent heat cascade table, which was a development from the Problem Table for continuous processes. Once Kemp and Macdonald developed the Cascade Analysis they applied it to two case studies to illustrate its use in distillation and reaction systems [58]. This work showed that time-dependent analysis gives a more detailed and rigorous assessment of the opportunities for heat recovery.

Kemp and Deakin continued with the development of cascade analysis [59–61]. They introduced a three-dimensional cascade plot (Fig. 3) to aid visualization of heat flows [59]. In their second paper the effects of rescheduling were evaluated [60]. The study showed that the individual time cascades could be different and the amount of direct heat exchange relative to heat recovered by storage could change. In short, the effect in energy terms of rescheduling could be calculated as it allowed some heat which had been previously recovered via heat storage to be recovered by direct heat exchange. Finally, in their third work Kemp and Deakin applied to a chemical batch plant the techniques that had been developed previously [61]. They also showed that rescheduling is a strategy that, combined with process integration techniques, may reduce energy targets, increase plant capacity, improve flexibility, etc.

This cascade analysis has been applied to different industrial situations. For example, it was applied to a batch process (speciality chemicals plant) and a building complex (hospital site). In both cases the cascade analysis identified new heat recovery projects which were more cost-effective than those obtained by older methods which had not taken variation over time into account [62].

Another example which tried to overcome the limitations of the TAM was the work done by Ivanov et al. [63]. They considered the

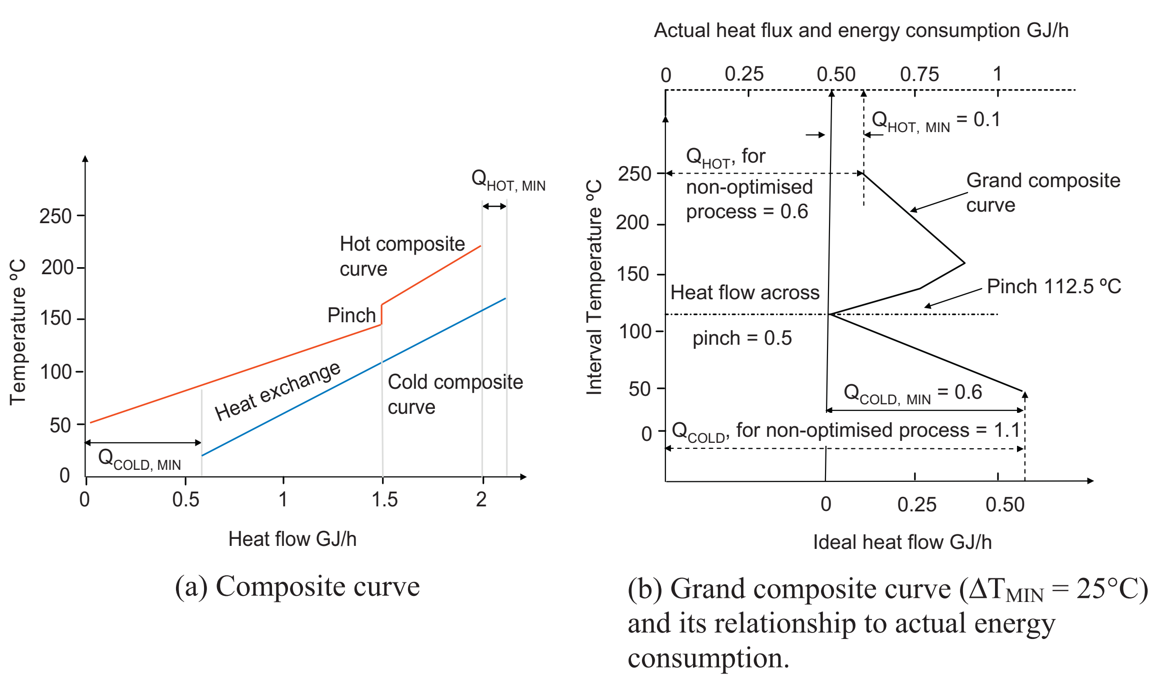

Fig. 2. Graphical representation of time-dependent heat cascade analysis [57].

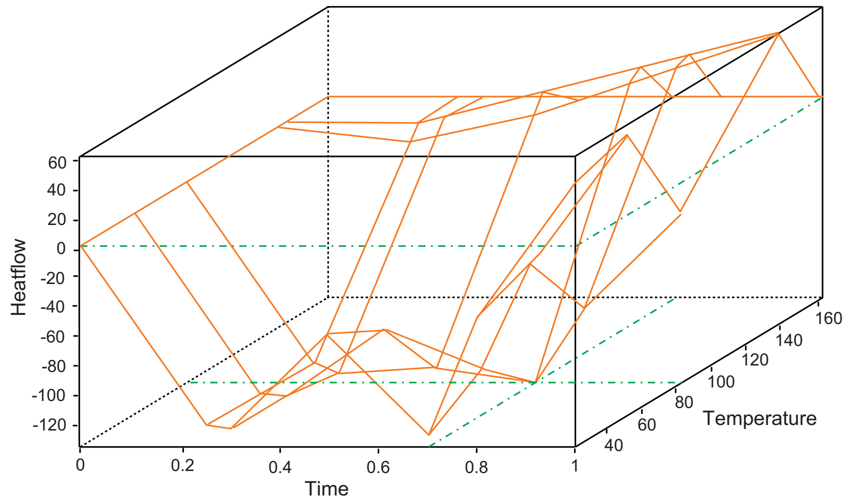

Fig. 3. Three-dimensional representation of cascade [59].

problem of batch reactor heating and cooling in a predetermined time interval. In order to resolve this issue they proposed a method of heating and cooling batch vessels which combined heat recuperation with temperature correction by means of external agents in such a way as to ensure full utilization in a heat system. Different types of heat integration schemes were discussed and these showed that the method proposed could be applied extensively in batch processing plant design and reconstruction with regard to their maximum heat utilization. This method was also applied in a hot–cold reactor system where the process did not allow fluids to be removed from the main vessels [64]. For that purpose, three different heat exchange arrangements were proposed. For each case, analytical relationships were obtained to define the vessel temperature time-course. The problem of the parametric synthesis of the systems under consideration was limited to finding both the design parameters of the heat exchange equipment utilized and the fluid flow rates of the fluids recycled. Later Ivanov et al. included some modifications in this method to obtain a synthesis of a heat exchange network system that ensured heating and cooling at minimum operation costs of a system of hot/cold batch vessels [65]. A generalised structure of a heat exchange network was presented, including: (a) heat integration block, (b) external heating and cooling blocks that permitted the utilization at intervals of all available external heating/cooling agents. Several arrangements of the heat exchanger network were considered. Synthesis was simply a procedure that involved determination of the heat exchange network structure and selection of appropriate heating and/or cooling agents and control action in such a way as to ensure minimum relative costs.

Additionally, Ivanov et al. analyzed the opportunities of heat integration in a system of two batch reactors operating in different time intervals through the use of heat storage tanks [66–68]. In the first part of the work the use of two storage tanks was discussed [66], the second part dealt with cases using one common heat storage unit [67], and the third part was devoted to the problems of synthesis and reconstruction of integrated systems with heat storage tanks [68]. In these works mathematical models which described the heat exchange in such system were developed. Temperature time-variation relationships as an explicit function of the main design and performance parameters were obtained. Finally, the temperature time–variation relationships of all processing fluids were defined explicitly as functions of the design parameters of the heat exchange equipment.

Ivanov and Bancheva also presented a new strategy directed at optimal reconstruction of heat integrated batch chemical plants [69]. This problem was formulated mathematically in terms of binary linear programming. It was suggested that the required production campaigns were obtained as a family of maximum independent vertex sets of an appropriate graph which determined essentially the superstructure of the schedules. The solution search tree procedure with bounds and branching function was used for its resolution. According to this stage of the proposed strategy, the aim was to create schedules which ensure, on the one hand, the producing of planning quantities of the products on the planning horizon and, on the other hand, the optimal conditions for heat integration by gathering in common campaigns appropriate heating and cooling processes.

In those years, another procedure was proposed by Hellsing and Thöne [70]. Their calculation procedure, named *OMNIUM*, was based on the *Hungarian Algorithm* to identify the set of heat exchanges which maximized heat recovery in a batch process. The problem was represented in a matrix where the hot streams were organised in columns and the cold ones were entered in rows. Each element of the matrix was assigned the maximum amount of heat that could be recovered if the corresponding match was selected.

Dynamic models were used by Papageorgiou et al. to describe the transient behaviour of the individual operations and the heat exchange network [71]. They consider the heat integration of two batch operations, the behaviour of which was described by mixed sets of differential and algebraic equations. The techniques presented generated the durations, starting time offset and total external utility demand profiles for the two operations in each such pair.

Boyadjiev et al. considered a technique for improvement of energy recovery in an existing biochemical plant [72]. The particular study case under investigation was the manufacture of the fermentation broth of antibiotics production. Their next step was to couple the above mentioned producer and consumer tasks in a direct heat integration scheme so as to reduce the overall demand placed on external utilities. Only the first part of the process was heat-integrated. Two distinct problems had to be solved: the first one was the optimal operation problem which aimed to ensure the optimal operation of the heat integrated scheme and the second was the scheduling problem, aiming at generating an appropriate schedule in order to achieve the required production rate. They formulated a mathematically optimal operation problem as a dynamic optimization with an objective function which attempted to minimize of the overall demand for external utilities. They modelled and solved the described optimal control problem using the DAEOPT dynamic optimization code.

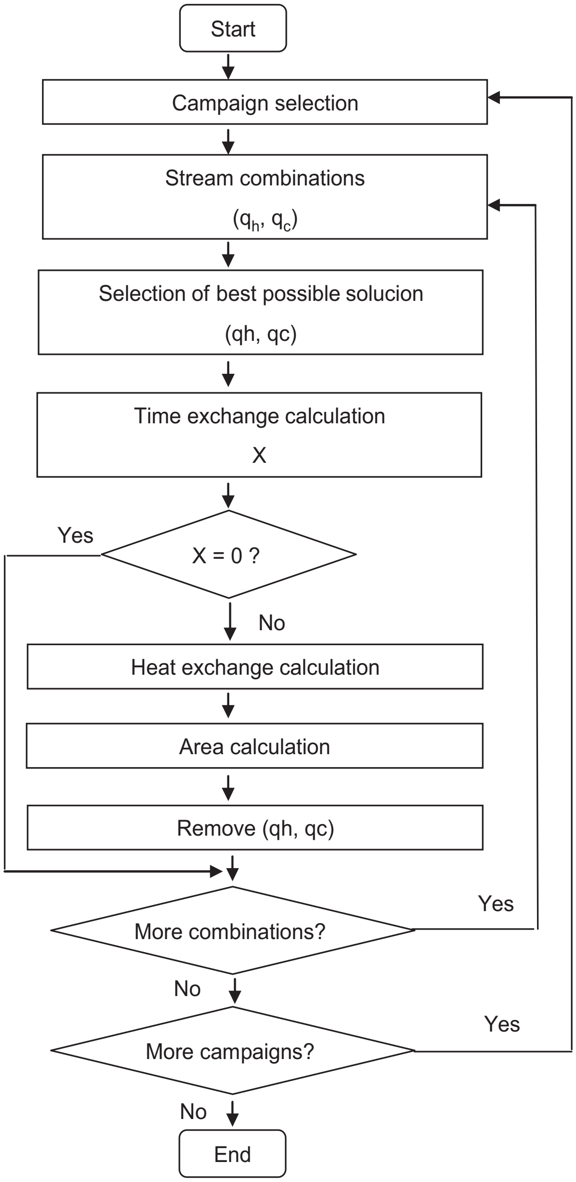

Fig. 4. Methodology proposed by Corominas et al. [44].

Once Kemp and Deakin had shown the crucial role that batch scheduling could play in increasing the efficiency of batch processes [59–61], several works have utilized rescheduling in heat integration of this kind of process. For example, Corominas et al. presented a methodology (Fig. 4) that contemplated systemization of rescheduling opportunities, altering the relative timing of the tasks involved in heating and/or cooling processes to reach the design of a minimum cost heat exchanger network and a heat exchange strategy for multiproduct batch plants operating in a campaign mode [44]. The objective was to maximize heat exchange in a pre-specified campaign of product batches. This objective was established mathematically on two levels that generated a master production plan which allowed the achievement of minimum time costs taking into account the variety of products to be produced by sharing the available equipment, utilities and production time resources. In order to demonstrate the applicability of their methodology (which involved task delays, waiting times, product stabilities and rescheduling of the batch sequence) Corominas et al. presented a simple case study [45]. This open modelling framework was combined with another mathematical model in order to reduce simultaneously waste production and energy consumption [73]. In this work, waste and energy minimization were treated as an integral part of the constrained production scheduling problem with limited resources.

Jung et al. presented in their work a mathematical model in terms of non-linear programming the objectives of which were to maximize heat recovery and reduce the batch cycle by means of optimal rescheduling [74]. In this work the mathematical model was applied to heat exchanges which occur as counter-current type. In the co-current type case the heuristic modified H/H was used to find the optimal match between hot and cold sources. All of the proposed heuristics aimed to reach maximum heat recovery in the batch plant.

Papageorgiou et al. proposed a systematic mathematical framework for scheduling the operation of multipurpose batch/semicontinuous plants involving direct and indirect heat integration [75]. The approach advocated takes direct account of the trade-offs between maximal exploitation of heat integration and other scheduling objectives and constraints (processing and storage equipment capacity, variation of the inventory of each material over time, utility availability...).

Lee and Reklaitis also described the possibilities of heat integration that are offered by scheduling [76]. In their work significant savings in the utility cost of batch plants could be obtained through heat integration coupled with the rescheduling of operation times. In this work, efficient scheduling models were developed for maximization of heat recovery for the case of no intermediate storage with holding time in cyclically operated single-product campaigns. In this development, the product recipe network was assumed to take the form of arborescence and each unit was assumed to be assigned to a single task. A MILP formulation was proposed to determine the operating schedule for maximum heat integration between the batch streams to reduce the utility consumption. Following on from their first work, Lee and Reklaitis relaxed the assumptions so that the heat exchange times were negligible compared with the batch processing time and that matches occurred between batches of material as they were transferred from unit to unit [77]. The extended formulation analyzed multiple heat exchange modes: countercurrent, cocurrent, and combinations of the two. The basic MILP formulation was further augmented to accommodate heat integration across independent cyclically operated batch production lines. A solution approach to the resulting large scale MILP formulation was developed, based on and demonstrated with two production line examples.

Another approach was proposed by Zhao et al. who presented a systematic mathematical formulation for the scheduling of some batch processes operated cyclically, involving the policy of no intermediate storage, but with direct heat integration [78]. The formulation was based on cascade analysis and led to a Mixed Integer Nonlinear Programming (MINLP) model. Extensive heat recovery from batch processes including the case of multiple stream matching could be accommodated by this model. An optimal schedule was found under the condition that heat was recovered in the mode of counter-current exchange, but other types of heat exchange could be introduced after rescheduling. Because of the computing difficulties for solving the MINLP model, some problem pre-processing methods for reducing the size of the model as well as several simplified solving strategies were proposed. This systematic formulation was subsequently utilized to define a three-step design procedure for the design of heat exchanger networks for batch/semi-continuous processes [79].

The time-heat cascade was also used to compare complex design procedures for both a continuous and a single product batch plant [80–82]. A FLOWTRAN program, which was a collection of blocks to simulate the process units, was prepared. In this program, each type of process unit was represented by a mathematical

model programmed as a subroutine. Each model subroutine was able to calculate its output streams, having been given the input streams and assuming there to be a steady state operation. Data used for energy integration were taken from the results of the FLOWTRAN simulation. In this study mathematical calculation of time-temperature cascades was carried out by spreadsheets [80]. The efficiency of energy integration was not the same for both types of processes (continuous and batch). The same example process was used to compare the net present worth of continuous and batch operation modes after including multi-purpose equipment [81]. Batch processes with multi-purpose equipment were usually less expensive than continuous ones because they have fewer process units (lower investment cost). Utility requirements, costs of raw materials and taxes remained the same even if merged operations were used. The batch process with multi-purpose equipment was to be favoured over the continuous one below 1300 tons of specialty chemical/year for the case study discussed. Only direct heat integration was considered, although there were possibilities for indirect heat integration to make use of a heat transfer fluid that could also be used to store energy in the three works [80–82]. The conclusions of these three works were that in the case of single-purpose equipment, the continuous plant was more profitable than the batch one for all capacities, but the batch process with multi-purpose equipment could be favoured over the continuous one when the equipment arrangement was appropriate (minimum number of process units and small size factor). In the second part of the paper, important economic factors (variable, fixed and equipment capital costs, product price) that had an influence on the net present worth of batch and continuous plants were discussed in detail. Variable costs had the greatest effect on the net present worth. Increased variable costs reduced the profitability of the batch or the continuous project [82]. Merging of tasks made the batch alternative more attractive at small production rates because economy of scale had a stronger effect on small size equipment. Merging could offset other disadvantages of batch processes; therefore it was cheaper to have one larger unit than many small units. The limiting capacity was determined where the batch process became more profitable than the continuous one, this depending on the process type and its annual costs.

Another example of utilization of methods that originally had been oriented to continuous processes and were later applied to batch processing was the work presented by Wilkendorf et al. These authors proposed a methodology whose objective was the automatic synthesis of complete utility systems with minimum annual capital and operating costs [83]. This methodology included the development of a flexible superstructure (Fig. 5) which took into account all the options contained in industrial processes. The flexibility of the methodology enabled it to be applied to both continuous and batch processes.

There were other studies that resolved the heat integration in batch processes question by establishing an objective that was to minimize the combined operating and annualized capital costs of the Heat-Exchanger Networks (HENs) for a class of multipurpose batch plants. For instance, Bancheva et al. considered operating and capital costs [84]. A mathematical programming approach was adopted leading to a MILP formulation. The plant was assumed to operate in a zero-wait overlapping mode. The formulation presented took account of the additional scheduling complications that arose out of energy integration between different products in the same campaign. In this study the campaigns were determined by means of a graphical theoretical approach.

Pozna et al. also minimized the total cost comprising operating and annualized capital costs, but they did so without rescheduling the whole production [85]. Their approach was suitable for existing batch vessel systems, where processes of cooling and heating were carried out simultaneously and were available in a given time interval and heat integration potential existed. For heat exchange equipment characterization, a generalised engineering parameter called power of the heat exchanger was introduced and used. This parameter incorporated the main process parameters such as heat transfer area, heat transfer coefficients, flow rates and heat capacities of streams. The problem was formulated in terms of MINLP.

3.2. Methods and models developed in 21st Century

The research carried out in this century has been focused on the establishment and improvement of the models and methodologies that had been proposed previously as well as the optimization of heat integration in batch processes through the development of new tools such as genetic algorithms, network evolution techniques... Moreover, there has been a significant increase in the utilization of thermal storage to improve heat integration in the discontinuous process.

For example, Uhlenbruck et al. improved the approach developed by Hellwig and Thöne [70] in order to obtain greater heat recovery [86]. These authors proposed applying the *OMNIUM* method recursively which led to a new heat matrix with the residual stream data. This has made heat exchange networks more complicated but it has increased their quality grade by around 20%.

Bozan and Borak tried to overcome the limitations of the method defined by Bancheva et al. [84], which was not practical for large numbers of products and vessels, as neither was it very suitable for computerized implementation. Bozan and Borak developed an interactive user-friendly computer program which asked for the necessary data for products and plant equipment [16]. The independent campaign sets were determined by using matrix operations. The potential locations of the heat exchangers were determined and this information was used for the MINLP problem of heat exchanger area optimization for multipurpose batch chemical plants. The grid search approach for solving the resulting highly nonlinear MINLP problem was proposed and solved by the modelling and optimization software GAMS/XA.

The initial methodology developed by Corominas et al. [44] was also modified and extended to incorporate detailed information on the energy consumption of the process at any point in time to attain uniform utility demands and to match utility resources and requirements [17]. Moreover, an objective function E, which included the total heating and cooling requirements of cold and hot streams of a given campaign, was considered in order to minimize energy consumption. The optimization procedure (Fig. 6) combined statistical and enumerative methods, the results of which were the proposal for different exchanges between process streams.

Chew et al. applied cascade analysis that has been proposed in the 90's [57], to study heat integration in a batch production of oleic acid (Fig. 7) from palm olefin using immobilised lipase [87]. In this case study, the maximum energy recovery objective was achieved without the use of heat storage. Firstly, the process was modelled in SuperPro Designer which is process simulation software to obtain energy and mass balances and the detailed scheduling of the batch manufacturing. Finally, the heat cascade technique was applied to target the minimum hot and cold utility consumption of the process. The development of BatchHeat software, whose aim was to highlight the energy inefficiencies in the process and thereby enabling the scope for possible heat recovery to be established through direct heat exchange or storage, represented another work which implemented cascade analysis [88]. The heat recovery potential was analyzed through the application of TAM and Time Dependent Heat Cascade Analysis. From the calculated heat cascades for each time interval, the program made it possible to determine minimum heat consumption by maximizing direct heat exchange and the visualization of the GCC for each time interval.

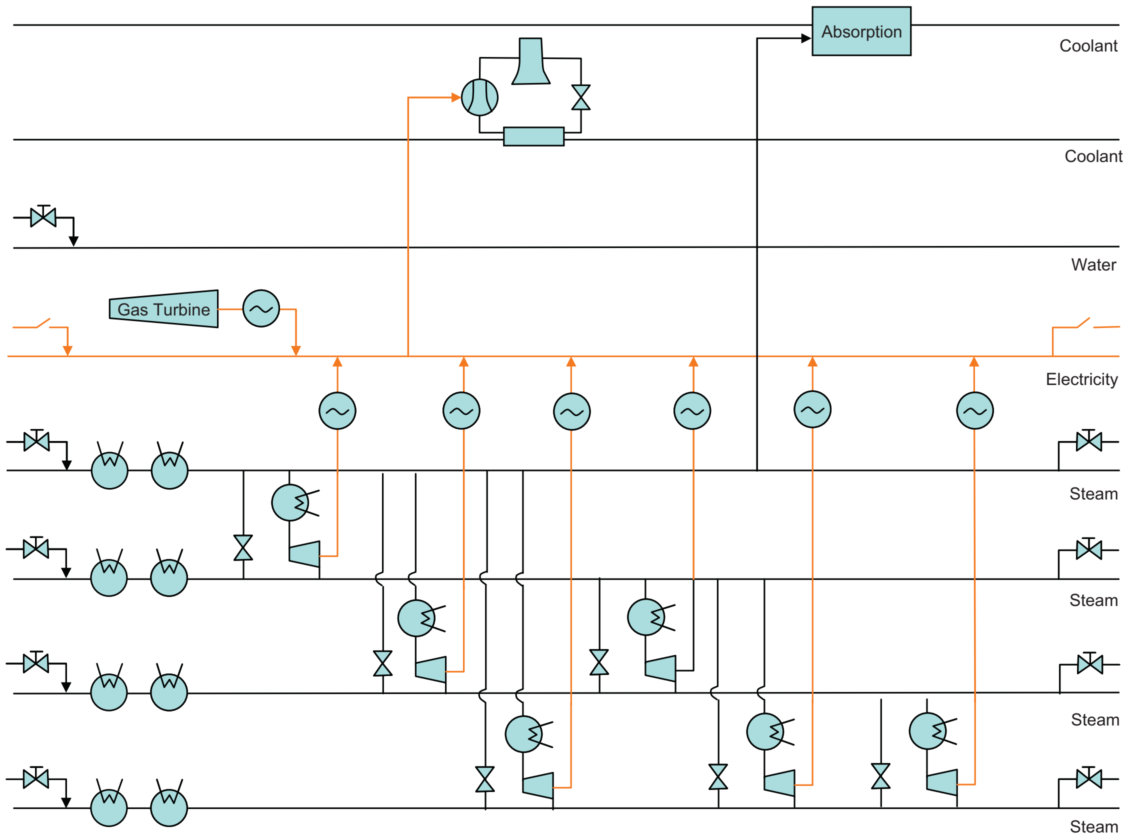

Fig. 5. Flexible superstructure [83].

Muster-Slawitsch et al. also applied cascade analysis [89]. Their work showed the development of a "Green Brewery Concept tool" based on three case studies. This tool included detailed energy balancing, calculation of minimal thermal energy demand, process optimization, heat integration and finally the integration of renewable energy based on exergetic considerations. The hot water management of a brewery was the key factor for integrating waste heat or new energy supply technologies. Morrison et al. developed a software package known as OBI [20]. Its objective was to reach a range of targets for different variables including hot and cold utility usages and heat exchanger network areas through heat cascade analysis calculations. The results from individual time intervals could then be combined to create the optimal overall design for the given process data. The overall design process was fully automated within the application.

Fritzson and Berntsson used a shaft work-targeting methodology also based on cascade analysis together with process simulation in HYSYS, which is an integrated simulation program [10]. A GCC was constructed for a modern food processing plant (Fig. 8), excluding excess heat from the heat pumps but including the heating

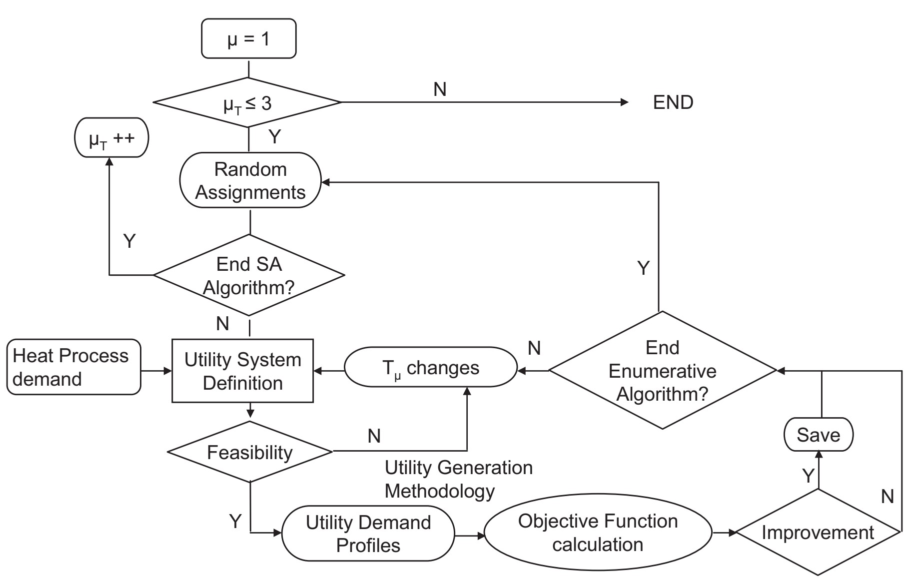

Fig. 6. Optimization procedure [17].

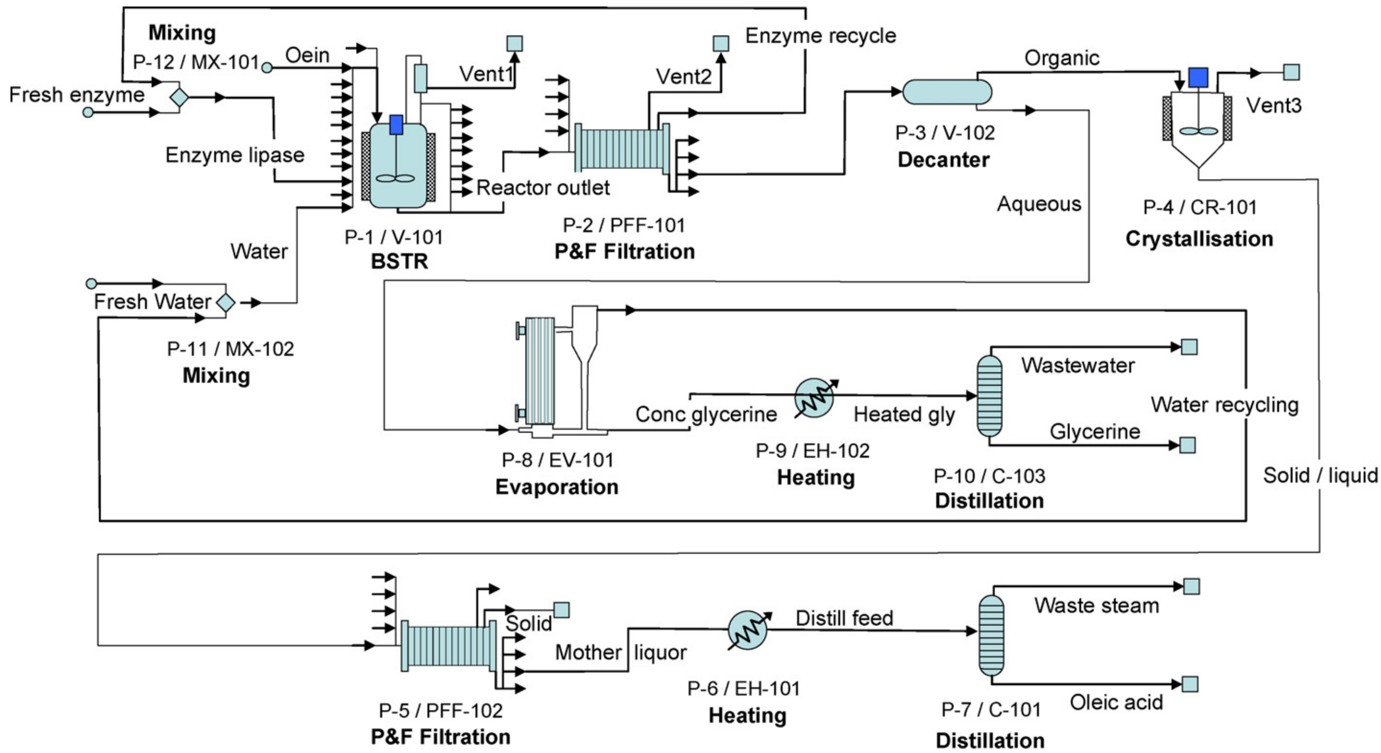

Fig. 7. Process flowsheet for oleic acid production [87].

needs in terms of water, process steam and comfort heating. After constructing the GCC, it was possible to study the potential for interaction between the streams mainly above ambient temperatures and the heat excess from the refrigeration plant. This interaction could be possible using a heat pump.

There are other works that have also incorporated energy integration in batch process scheduling [8,19,90–91]. The first one was done by optimizing the schedule to simultaneously minimize an economic objective such as make-span and utilities [8]. The authors proposed a multi-objective framework for simultaneous process scheduling and utilities minimization. They applied Kemp's batch pinch analysis [51] to design an optimum heat integration network. Both the make-span and utilities were used as objectives for manipulating the decision variables to obtain Pareto-optimal solutions. Heat integration was carried out on each of the scheduling solutions. This was done by pairing the process hot streams that require cooling and the cold streams that require heating to reduce the overall utilities requirement. The optimization was performed in a three-stage procedure: MILP for minimizing the make-span, MILP for utilities minimization and simulated annealing for multi-objective optimization. In the work presented by Halim and Srinivasan the method was based on a sequential framework, where the overall problem was decomposed into two sequentially solved problems of scheduling and heat integration [19]. First, the schedule was optimized to meet the economic objective such as make-span or profit. Next, alternate schedules were generated through a stochastic search-based integer cut procedure that added further constraints to the scheduling formulation. Finally, the TAM and TSM were applied to each of the resulting schedules to establish the minimum utility targets. The mathematical model used in this work was the continuous-time model reported by Sundaramoorthy and Karimi [92]. Later, Halim and Srinivasan extended their technique to carry out water reuse synthesis simultaneously (Fig. 9) [90]. One key feature of this method is its ability to find the heat integration and water reuse solution without sacrificing the quality of the scheduling solution. Finally, Adony et al. incorporated heat integration in batch process scheduling using the S-graph approach to represent scheduling and the corresponding heat exchanger network synthesis problem [91]. This procedure took the scheduling and the heat integration into account simultaneously instead of consecutively. This method was based on combinatorial algorithms and its objective was to minimize the utility usage in the system. The results of this work showed how utility usage could be reduced considerably with just a slight increase in production make-span.

Simpson et al. developed a mathematical model to estimate total and transient energy consumption during the heat processing of retortable shelf-stable foods [93]. This model was also useful in searching for optimum scheduling of retort battery operation in the canning plant, as well as in the optimizing process conditions, to minimize energy consumption, but also to identify feasible variable retort temperature profiles.

Majozi presented a continuous-time mathematical formulation for the optimization of heat integrated batch chemical plants [6]. The developed model had three major advantages. Firstly, it was based on a continuous-time framework (Fig. 10), which resulted in far fewer binary variables than the discrete-time formulation. Secondly, it was not strictly constrained regards time. Thirdly, the objective function could assume several forms depending on the nature of the application, such as minimization of make-span, maximization of profit, minimization of capital cost investment, etc. Moreover, the heat integrated tasks could either belong to the same process or different processes within reasonable proximity. This methodology was an extension of a previous scheduling model that Majozi and Zhu had proposed [94]. That previous model had used a state sequence network representation.

The methodology developed by Majozi [6], which was only aimed at direct heat integration of batch plants, was extended to include heat storage [18]. The main advantages of this methodology were that the start and end times of processes did not need be specified a priori and it required very few binary variables due to uneven discretization of the time horizon of interest. The extension

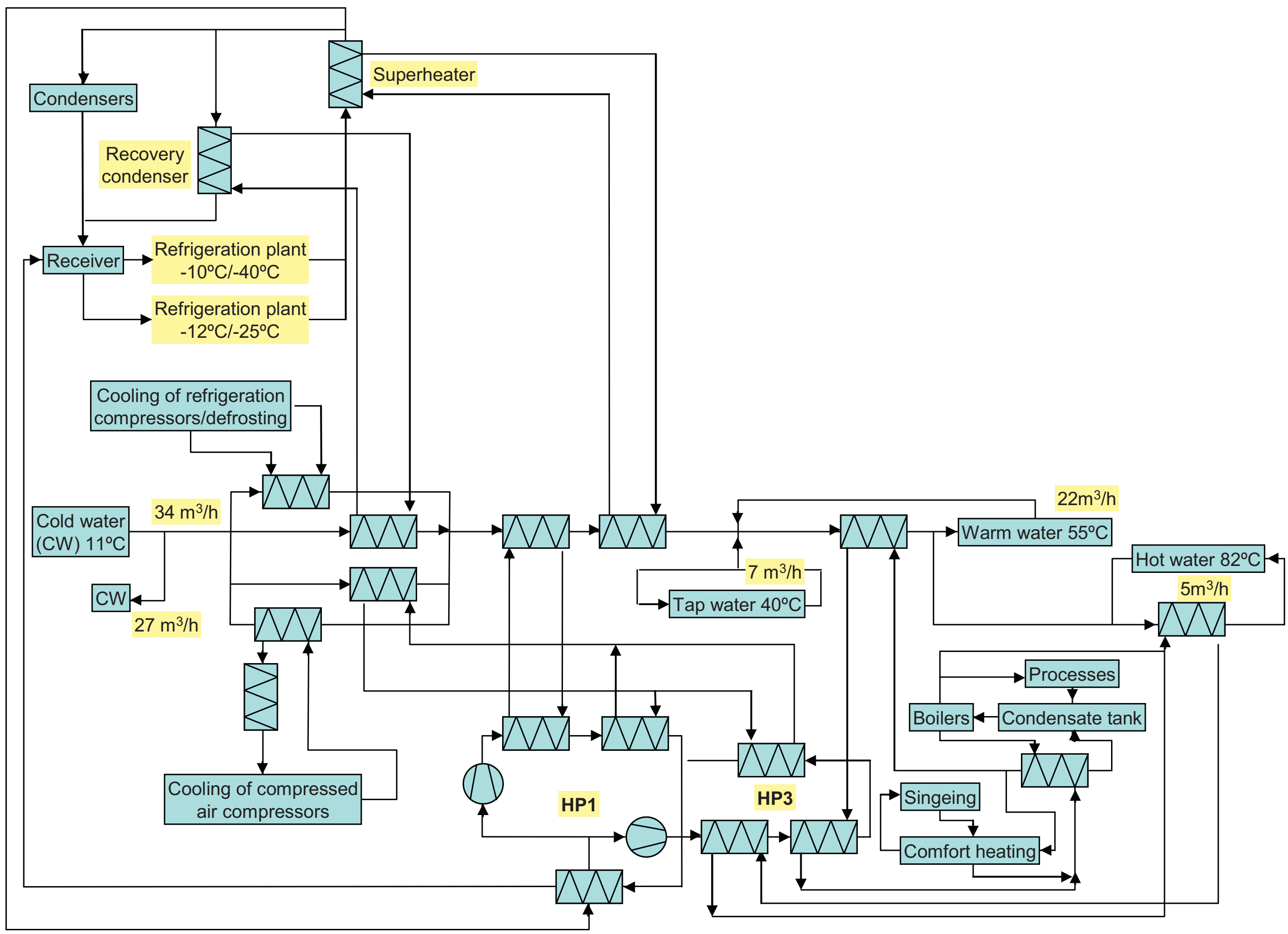

Fig. 8. The heat recovery system in the studied slaughter and meat processing [10].

made possible the inclusion of heat storage as a possibility for saving more energy and allowing overall flexibility of the process. The mathematical model was linear, which implied that the solution corresponding to a predefined size of storage was globally optimal. This MILP model which was more suitable to multiproduct was extended to multipurpose batch facilities, with optimisation of the heat storage capacity available as well as the initial temperature of the heat storage medium [95]. The resulting model exhibited MINLP structure, which implied that global optimality could not generally be guaranteed. However, a procedure was presented to find a globally optimal solution, even for nonlinear problems. Heat losses from the heat storage vessel were also considered.

Behdani et al. also proposed a mathematical model on the basis of continuous-time representation to accommodate optimization of utility (especially energy barriers) demands and supplies of batch processes [96]. Their work included a first formulation that was a scheduling model with the objective of product sales' revenue maximization, without taking energy into account, and a second formulation that was a scheduling model which considered utility aspects in its constraints (not in the objective function). The continuous-time formulation was an extension of the work presented by Ierapetritou and Floudas [97] for scheduling of mixed batch/continuous processes.

Chen and Chang formulated a new MILP for modelling the short-term and periodic scheduling problems with direct heat integration in batch plants [9]. The proposed formulation was based on the continuous Resource-Task Network (RTN) representation. In addition, they also attempted to generalise the heat-integration model originally proposed by Majozi [6]. For instance, a set of shifting parameters was introduced in order to handle the cases when the start time of heat integration was shifted from the beginning of a task. This was very useful in some arrangements, such as when pre-heating is required before the real heat integration. Although this work mainly studied the possibility of direct heat integration, it was also possible to include the indirect heat integration simultaneously by incorporating mass and energy balances for each point in time.

The RTN representation was used to model the scheduling problem by Castro et al. too [98]. The goal of their work was to find the optimal schedules for different scenarios of steam availability in a pulp cooking process which consisted of a set of four parallel batch digesters with different capacities. All process units were modelled through the use of the general purpose modelling, simulation and optimization tool, gPROMS. The mathematical formulation that they developed was based on a discrete representation of time, where the time horizon was divided into a number of intervals of equal and fixed duration. Operational constraints were used to impose certain restrictions on the variables. Most of these were related to the number of production cycles to be studied.

The work of Ryu and Pistikopoulos introduced a parametric programming technique for reducing economic costs for a special type of batch operation in which products were processed without being stored (Zero-wait) [99]. The main advantage using the proposed technique was that a complete map of optimal schedules was obtained as a simple function of varying parameters.

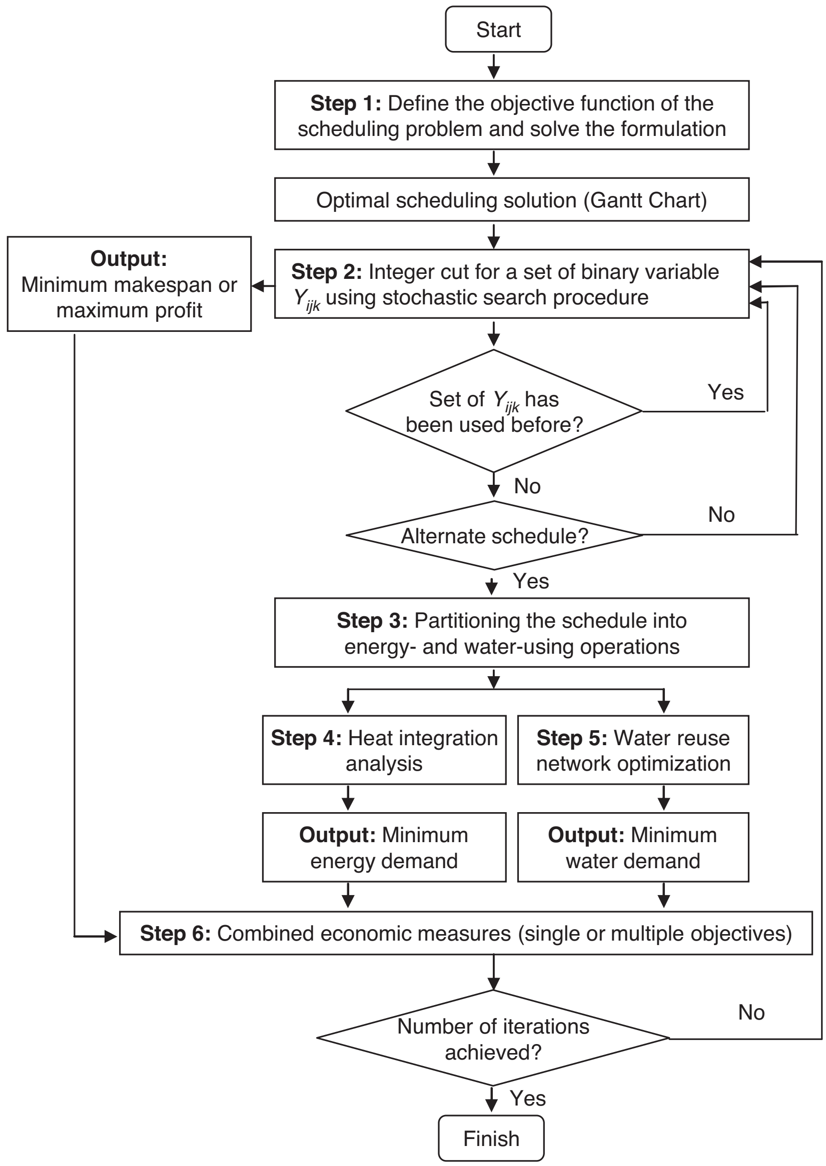

Fig. 9. Integrated scheduling and heat and water integration Framework [90].

Although since the 90's, most works about heat integration in batch processes have proposed specific methods for batch processing, Pourali et al. developed a new systematic method (time interval combination) that consisted in extending the concept of problem table decomposition for the thermal integration of continuous processes to batch processes (Fig. 11) [100]. This approach considered process constraints (operational and economic) through defining individual time and heat intervals. Time interval combination achieved a higher level of heat recovery through rescheduling in batch processes. The main advantages here over other methods were as follows:

(a) It was a systematic design technique that could be utilized to find the optimum cost and plant operation schedule for better thermal integration.
(b) It led to the reduction of the batch operation period, which resulted in an increase in production capacity and annual profit. The proposed method could easily be coded on a computer program. In this code, the correction factor was a good statistical tool for considering feasibility of each time interval combination by reducing the probability existence of time interval combinations in a process where time intervals were both long and frequent.

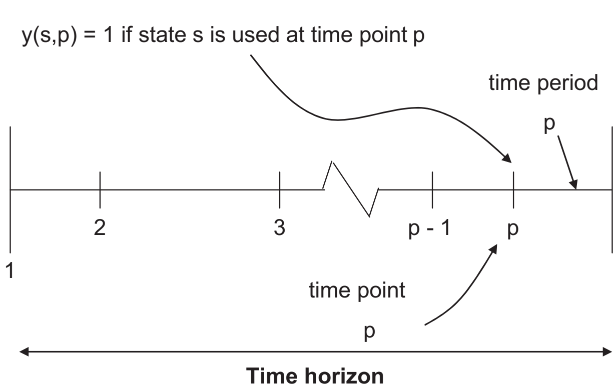

Fig. 10. Continuous-time framework [6].

Becker and Maréchal also proposed a new methodology which could be used to identify the required heat transfer units when

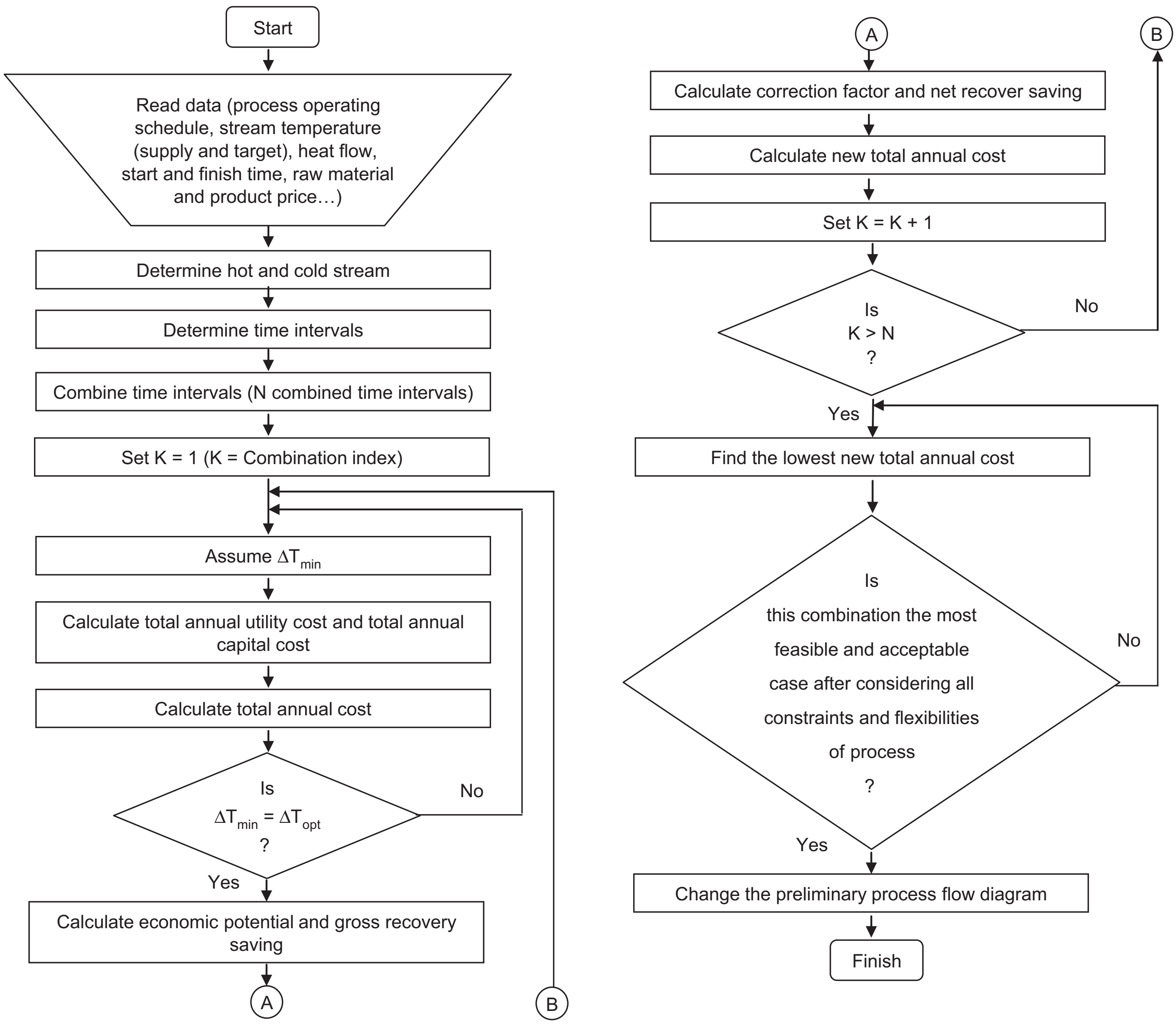

Fig. 11. Computer flow diagram for determining the best combination of time intervals in batch processes [100].

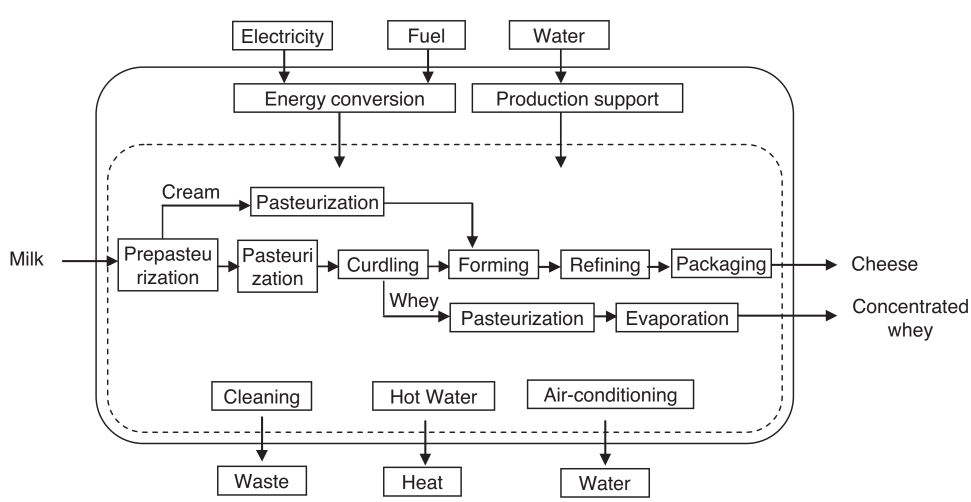

Fig. 12. Process of cheese factory [102].

solving continuous and batch process integration [101]. The application of this method in batch process could be done considering the non simultaneous operations in different sub-systems for which the direct heat exchange was not possible. The problem was solved in several steps. In the first step, a MILP problem without restricted matches was solved. This defined the optimal flow rates in the energy conversion systems (utility system) and the minimum operating costs. The energy penalty was then calculated by solving a MILP problem including restricted matches between sub-systems but with no possibility to integrate heat transfer technologies. In the next step the envelope composite curves were computed by using a MILP problem including industrial constraints and fictive hot and cold streams for the heat transfer system. The identified HTUs were then added in the list of hot and cold streams and a final MILP problem including restricted matches and chosen optimal heat transfer units could be resolved. Their flow rates were calculated by solving again the MILP problem. To demonstrate the suitability of this methodology in heat integration of batch process Becker et al. analyzed the process integration in a cheese factory (Fig. 12) [102].

Barbosa-Póvoa et al. presented a mathematical formulation for the detailed design of multipurpose batch process facilities with heat integration based on a pre-defined objective [15]. The problem was formulated as a MILP problem where binary variables were introduced to characterize operational and topological choices. The objective function was based on the maximization of the plant's profits. These authors extended this model for the design of multi-purpose batch process facilities with heat-integration and economic savings in utilities [21]. In this second work they considered the consumption of external and internal utilities and the possibility of having direct heat integration within the plant. The formulation of the design of batch facilities with heat-integration was developed using the Maximal State Task Network representation. Their objective was to determine the optimal selection of the equipment units and the network of connections, the associated plant operating schedule and the plant heat-transfer policies, as well as associated utilities requirements and the design of the associated auxiliary heat-transfer equipment structures and auxiliary network circuits. They defined two objective functions: maximum profit and minimum capital cost in order to reach the aims of the work.

Ruiz and Medeiros also established maximum profit as an objective function [103]. They described and modelled Vessel Network Systems of a quaternary separation under fixed vessel hold-ups, a fixed number of stages per cascade and fixed heating power. This problem, unconstrained by means of transformed variables, was put together with a Price Function for product valuation.

Liu et al. formulated a nonlinear programming model targeting minimal annual total cost instead of maximum profit [104]. This model could minimize simultaneously operation cost for utilities as well as capital cost for heat exchanger units. The global optimal solution was obtained with a parallelized genetic-simulated annealing algorithm (GA-SA) developed by them. Maiti et al. also aimed to reduce the total annual cost [105]. They proposed a novel heat integrated batch distillation column (HIBDC) to improve the thermodynamic efficiency and reduce the total annual cost. They investigated the feasibility of energy integration and selected the value of operating compression ratio; a detailed analysis was conducted in terms of energy consumption and economics.

Another alternative was presented by Mujtaba et al. [11]. They demonstrated the value of an integrated approach which coupled the manufacturing unit scheduling with the utility system's operational planning. Contrary to the traditional reasoning of placing the emphasis solely on production (manufacturing unit) and treating the utility system as a subsidiary unit, it was vital to develop an integrated approach which simultaneously carried out the task of the scheduling of manufacturing unit and the operational planning of utility system. A discrete-time MILP model was developed to compare traditional and integrated approaches. The implementation of this integrated approach in a real company required: (a) extensive use of computer aided tools and (b) enhanced communication between the management of both manufacturing unit and utility system.

In their work Foo et al. extended the minimum unit targeting and network evolution techniques that were developed for batch mass exchange network [38] into batch HEN [106]. It was shown that in order to simplify a batch HEN with the network evolution techniques, a thorough analysis had to be carried out across all time intervals of the batch process.

Although direct heat integration has been the most commonly implemented way to reduce energy demand, there are several studies which have evaluated the possibilities that heat storage offers. For instance, Krummenacher and Favrat proposed a procedure to determine the minimum number of heat storage units [48]. These authors described a new systematic procedure, supported by graphics, which made it possible to determine the minimum number of heat storage units, assuming there to be vertical heat transfer, and their range of feasible operation as a function of the amount of heat recovery. A set of heuristic rules were proposed to screen major options corresponding to minimum cost solutions and a total annual costs versus heat recovery diagram helped in understanding the trade-offs and highlighted the key role of constraining supply temperatures and the resulting storage pinches in generating local minimums. Finally, these authors defined a set of preliminary guidelines to extend the methodology to mixed direct–indirect heat integration.

The aim of Peredo et al. was also to implement mixed direct-indirect heat integration. They developed a computer application which permitted the integration of thermal storage in the heat recovery network from a hospital through the design of superstructures [107]. This application used a spreadsheet that offered all the data of the superstructure (hot and cold streams, storages, heat exchanger area...) in graphic format, (Fig. 13).

Krummenacher et al. also explained the feasibility of optimizing with genetic algorithms the heat integration of batch processes [49,108]. One of the strengths of genetic algorithms is the capacity to accommodate heuristic rules, which can be introduced into the model. The GABSOBHIN project aimed at the development and implementation of a synthesis and optimization method, based on genetic algorithms, for the heat integration of batch processes. Two heat integration modes were addressed: (a) indirect heat recovery using intermediate heat storage; (b) direct heat integration (by means of a direct batch heat exchanger network) accounting for the possible re-use of heat exchanger units across time slices. Comparison of two optimization strategies showed a preference for a two-step optimization scheme [108]. In his thesis Krummenacher addressed both indirect heat integration (i.e. resorting to intermediate heat storage) and direct heat integration (i.e. heat exchanges between coexisting process streams) of batch processes. Tools and methods for the targeting of these two limiting cases of heat integration were proposed, and completed by the development and the application of an automatic design & optimization methodology using the *Struggle* Genetic Algorithm (GA) (Fig. 14). Two models of indirect heat recovery schemes using fixed temperature/variable mass Heat Storage Units (HSUs) suitable for a GA based optimization were developed and implemented in *Matlab*. A first model considered a closed storage system (i.e. the standard case, where storage fluid was confined in the HSUs), while the second was based on an open storage system, in which the storage fluid was a process fluid (most generally process water) which entered the storage system, was heated (or cooled) and left the HSUs whenever these process streams were required. When the total batch costs were used as the objective function

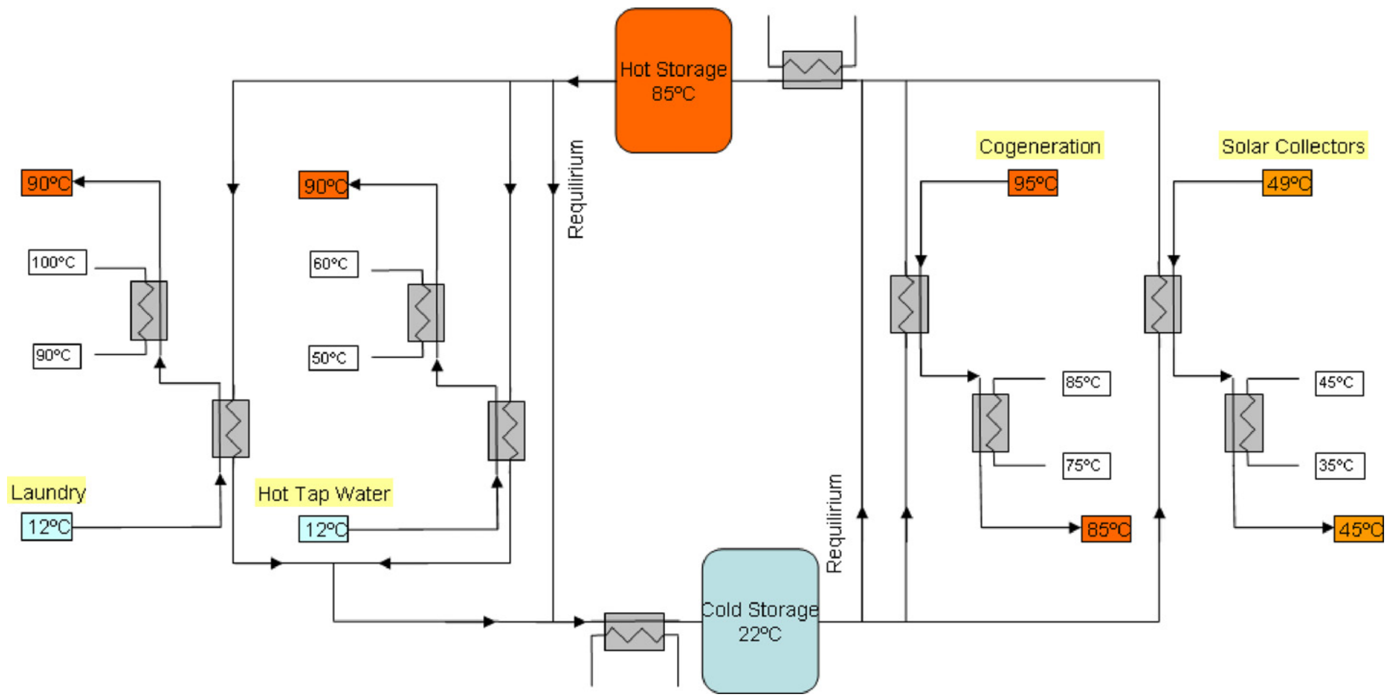

Fig. 13. Graphical representation of the obtained superstructure [107].

throughout the optimization process, the replacement strategy applied by *Struggle* prevented the development and the progressive improvement of individuals featuring a high heat recovery so that the delivered solutions actually stuck at sub-optimal regions.

Heat storage also was utilized by Martin et al. to reduce energy consumption of a milk powder plant in New Zealand [109]. The approach studied the possibilities offered by a heat recovery loop and stratified tank to implement indirect heat integration. This work used modified source/sink composite curves to rapidly determine the amount of maximum heat recovery. The results of this paper showed that heat recovery was increased when thermal storage was incorporated into the heat recovery loop. However, it also

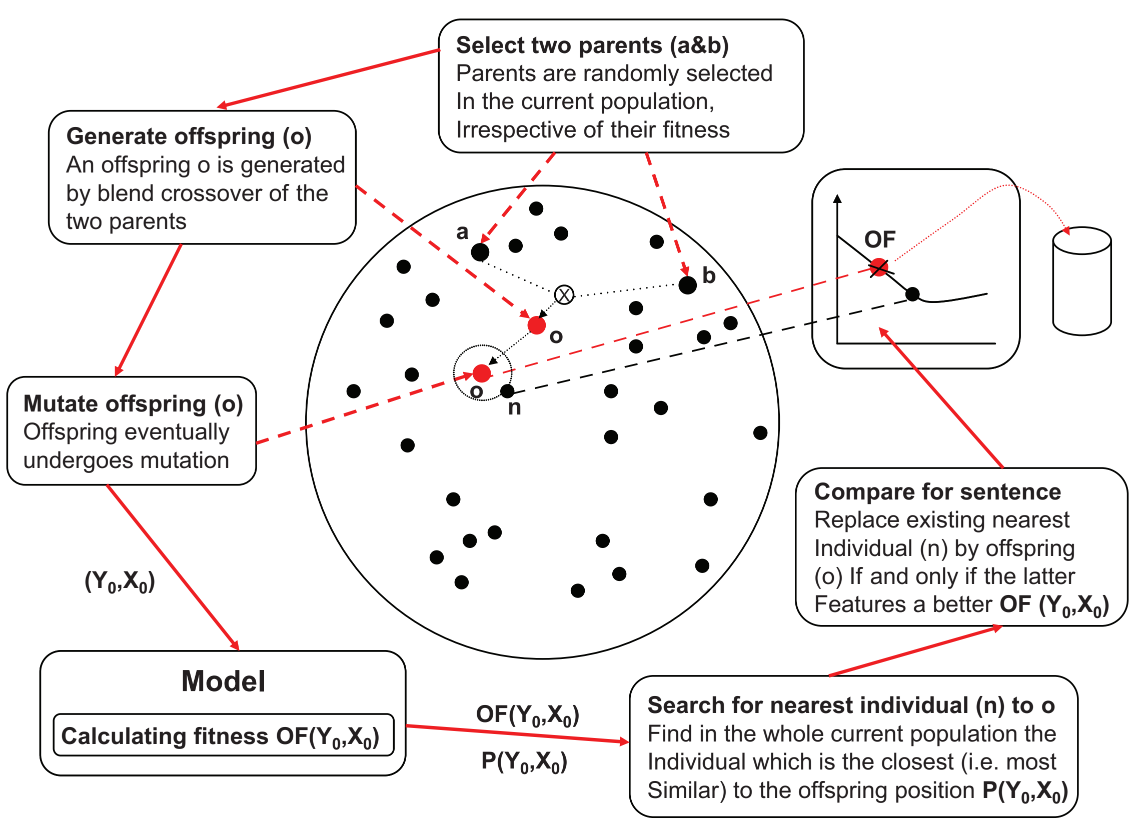

Fig. 14. Reproduction strategy of the Struggle GA (in this context, $P(\ldots)$ means the position of an individual in the solution space [108].

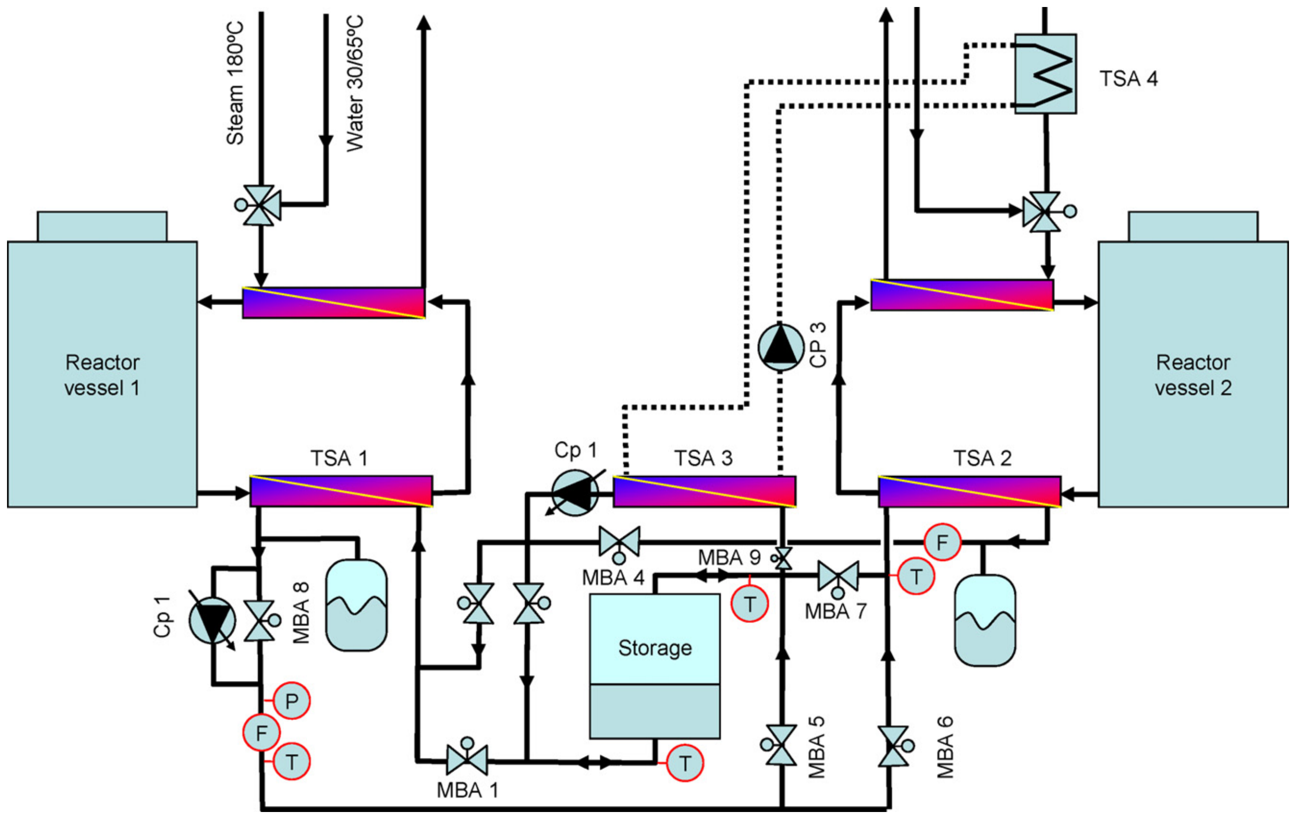

Fig. 15. Process scheme for a thermal storage system connected to the two existing batch reactors [111].

was concluded that the amount of additional heat recovery was very dependent on the size of the tank and the dynamics of the available sources and sinks. The study also showed that the variation in the temperature of the hot fluid in the recirculation loop could increase the maximum amount of heat recovery depending on which condition the site was operating under.

Chen and Ciou proposed an iterative method for designing an indirect heat recovery system including the associated variable-temperature storage in a batch plant [110]. This work was a direct extension of another where they relaxed the restraint of constant temperature for HTM in each storage tank to magnify the heat recovery potential [7]. The design problem was formulated as a MINLP based on proposed superstructures. A novel iterative solution strategy for setting the variable temperatures of HTM in storage was provided by linking the network optimization tool (a GAMS program) and the stream temperature simulation software (a MATLAB program). Modified superstructures from their previous work [7] were presented for modelling the time-dependent heat exchange operations.

Boer et al. evaluated the technical and economic feasibility of an industrial heat storage system [111]. The study focused on the integration of a heat storage system within an existing production facility of organic surfactants (Fig. 15). Three different thermal storage systems with operating temperatures from 110 °C to 160 °C were designed to store the heat released during the exothermic reaction phase and re-use the heat for the preheating of the reactants in the following batch. The first system used a Phase Change Material (PCM) contained in metal balls with an assumed phase change temperature at 140 °C. The second system used a concrete volume as a sensible heat storage material and the third system was also based on concrete, but with a doubling of the storage capacity. A dynamic simulation was performed of a reference cycle of a batch reactor coupled with a thermal storage system to calculate energy savings for preheating of the reactants. It was necessary to enlarge the storage capacity of the PCM system in order to obtain a heat transfer rate matching the conditions of the actual process. The calculated energy savings for heating of the batch reactors was 50–70%, resulting in financial savings. Simple pay out time was higher than 10 years, with the best result for the concrete heat storage. The bare cost of the thermal buffer was 15–30% of the total capital investment. Because the cost of integration of the storage system into an existing facility was a large part of the total cost, it was recommended that the use of thermal storage systems for grass-roots situations be evaluated. This work showed the crucial role that PCMs could play in batch processing, and not only in building [112], where this kind of material is most commonly applied.

Recently, Tokos et al., in order to comply with the specific conditions of a large, beverage plant [113], slightly modified the results obtained by Lee and Reklaitis [76,77]. In the basic formulation proposed by Lee and Reklaitis the objective function had been defined as a fraction of the utility savings to the utility required per individual batch without heat integration. In order to introduce an economic trade-off between the utility savings and investment costs of the heat exchanger area, the objective function was transformed into a net present value function which included annual savings in utility costs, and the annual investment cost of the heat exchangers. The proposed heat integration scheme and the selected cogeneration system could improve a company's economic performance and reduce its environmental impact. Tokos et al. studied a large beverage plant to analyze the possibilities: (a) of heat integration between batch operations and, (b) of the installation of a polygeneration system to produce electricity, and heating and cooling at the site.

The heat exchanger design and operation has a critical unresolved problem named fouling. This problem affects nearly every plant relying on heat exchangers for its operation and introduces costs which are related to energy conservation, operation and

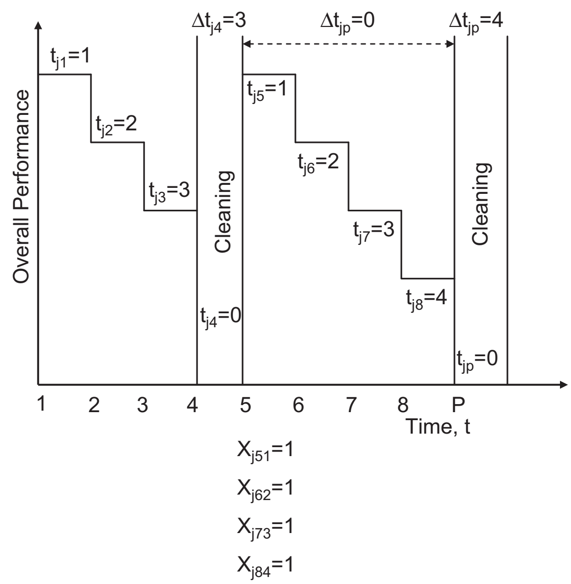

Fig. 16. Graphical illustration of the cleaning constraints [114].

capital investment. The common practice to mitigate fouling has been the implementation of cleaning in-place operations. For this reason, Georgiadis and Papageorgiou argued in their work that heat integration and fouling aspects must be considered together with the production scheduling problem through the definition of cleaning constraints (Fig. 16) [114] that they had not considered in a previous work [115]. The cost of external utilities and cleaning must be incorporated within the overall economic objective function to maximize the net production value over a given time horizon. These authors demonstrated how fouling aspects could be incorporated within a general mathematical formulation that Papageorgiou et al. had proposed previously for the scheduling and heat integration of multipurpose plants [75]. The objective of Georgiadis and Papageorgiou in [114] was the selection of the schedule that maximized an economic performance measure taking into account the value of products, and the cost of utilities and cleaning.

4. Conclusions

The papers analyzed have shown that the interest in energy recovery in batch processing began in the 80's. In those years the research was based on the change and adaptation to the batch process of methods which had been developed previously for continuous ones. These methods were mainly graphical.

In the following decade, the giant developments in computing motivated the design of mathematical algorithms which allowed the energy integration of the discontinuous process to become more complex. Moreover, in this decade the authors started to use rescheduling as a tool which could help to obtain energy recovery in a discontinuous process. In addition, it was in this period when environmental aspects related to efficient use of energy began to be considered. Different authors indicated that the implementation of new strategies to reduce energy demand through waste heat recovery offered up a great chance to meet the requirements of the Kyoto Protocol.

The research carried out in this century has been focused on improving the optimization of batch processing through the use of new tools such as genetic algorithms, network evolution techniques...and the utilization of thermal storage. Moreover, it has produced an increase in the creation of new integrated approaches which combine heat integration, water recovery and/or a drop in the demand for raw materials. There are some works that have described new aspects that should be analyzed in the design of heat integration networks, such as fouling, which could considerably reduce the heat exchange or economic issues that help towards attaining a competitive industrial process.

The success of heat integration in batch processing should make it possible to define new strategies whose objective represents the result of considering not only energetic aims, but also the reduction in resource demand. This aim implies the development of methods and tools that support decision-making when designing a more efficient discontinuous process.

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